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SUMMARY OF THE NONCONFORMING TITANIUM TASK FORCE ACTIONS TO RESOLVE AIRCRAFT SAFETY ISSUES DUE TO IMPROPERLY SUBSTITUTED MATERIAL

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EXECUTIVE SUMMARY

Titanium material used in aerospace applications was found to be nonconforming to various military, industry, and professional society material specifications due to a common industry practice of cutting (versus rolling) billet material and certifying it as meeting bar or rolled plate specifications. A USAF task force was assembled to address the potential safety and readiness impacts to USAF aircraft and to coordinate findings and recommendations with other Services and Agencies investigating impacts to aircraft and other products. This report summarizes the work undertaken by the nonconforming titanium task force from August 2009 to December 2011.

INTRODUCTION

In November 2003, Boeing conducted an internal investigation of Western Titanium (WT) supplied components wherein Boeing determined that WT had supplied bar material but had certified it as plate material. In other words, the material had been improperly certified. On 14 April 2004 Boeing issued a Government–Industry Data Exchange Program (GIDEP) Problem Advisory (reference 1) against WT for titanium rolled plate and bar. (A brief background on titanium fabrication and product forms can be found in the appendix.) Boeing amended the original GIDEP on 15 July 2004 with additional exhibits that were inadvertently omitted from the original document (reference 2).

Shortly after the original GIDEP was issued, Defense Contract Investigative Services (DCIS) began an investigation into WT's practices and subsequently seized several F-15 engine mounts that had been fabricated with WT material. The blueprint material for the engine mounts was Ti-6Al-6V-2Sn titanium¹ plate. At the request of DCIS, the Air Force Research Laboratory (AFRL) Materials and Manufacturing Directorate performed tests of the engine mounts to determine if the material met the specification requirements. Three engine mounts were seized in 2004 and were examined in 2005 by AFRL for mechanical and metallurgical properties. The results of this examination are documented in reference 3. An additional 18 F-15 engine mounts (9 ship sets) were seized in 2006 from USAF spares inventory, and again AFRL performed mechanical testing of these parts in 2006 with the results documented in reference 4.

On 27 July 2007, AFRL briefed the Aeronautical Systems Center Engineering Directorate (ASC/EN) Technical Advisor for Aircraft Structural Integrity and Structures Branch personnel on the F-15 engine mount test results. The meeting resulted in the formulation of a "path-finder" approach to continue to work with Boeing to resolve differences of opinion regarding the test results. From these discussions, AFRL conducted 18 additional mechanical tests and 17 additional crack growth tests of material from the F-15 engine mounts. Testing was accomplished during 2008 with the results published in reference 5.

The AFRL testing concluded that the measured material properties were inconsistent with plate, since the 2006 and 2008 tests showed significant differences in mechanical properties from same material from the same parts in orthogonal directions. In parallel with the test program, AFRL reviewed processing paperwork for the engine mounts. The review clearly showed that some of the material had only been forged and had not gone through a rolling process to convert it to plate. The processing paperwork and test results led AFRL to conclude that reforging stock (also known as billet) material was substituted for plate in the fabrication of at least one engine mount. As described in the appendix, reforging stock is an intermediate product form not intended for finished

¹ Ti-6Al-6V-2Sn denotes a titanium alloy with 6 percent aluminum, 6 percent vanadium, 2 percent tin, and the balance (86 percent) of titanium. This nomenclature is usually shortened to Ti-6-6-2.

products since it has not undergone the necessary thermomechanical steps to achieve the required material properties. Bar material properties are near, or in some cases better, than plate material properties, and would not have yielded the results obtained during AFRL testing of F-15 engine mounts if bar had been substituted for plate.

In summary, the AFRL tests in the 2006 to 2008 timeframe subjected 86 specimens to tensile testing and 37 specimens to fatigue crack growth testing. A high percentage of material failed to meet AMS-T-9046 specification (reference 6) minimums: 32 specimens (37 percent) did not meet the F_{tu} (ultimate tensile strength) specification minimum, and 19 specimens (22 percent) did not meet the F_{ty} (yield tensile strength) specification minimum. Typical F_{tu} and F_{ty} values for properly processed Ti-6-6-2 material are typically 10 ksi higher than minimums². The worst case measured F_{tu} was 8 ksi (5 percent) and F_{ty} was 3 ksi (2 percent) below minimum. Fifty-nine specimens (69 percent) exhibited large deviations from the typical elastic modulus value (E) in the Metallic Materials Properties Development and Standardization Handbook (MMPDS, reference 7). This deviation in elastic modulus also provided another strong indicator of improper processing. Mean fatigue crack growth rates obtained from 37 specimens were approximately two times faster than plate.

Based on these test results, ASC/EN issued an Airworthiness Advisory in March 2008 (reference 8) to all USAF program offices and Air Logistics Centers (ALCs). The advisory requested that program offices review all fracture critical and safety-of-flight parts to determine potential safety and service life impacts if reforging stock/billet material had been substituted for plate.

In August 2009, Air Force Materiel Command (AFMC) learned that additional evidence had been found that reforging stock material had been substituted for plate. The investigation discovered that billet material had been mechanically cut or sawed to sizes representative of bar and plate material and improperly certified as bar or plate. This finding confirmed previous AFRL conclusions. It also raised safety concerns since billet material theoretically had lower material properties than bar or plate material and was now known to have been used in the fabrication of some parts used in USAF aircraft.

² ksi is engineering shorthand for one thousand pounds per square inch (psi).

TASK FORCE

As a result of the unknown safety concerns with substituted material, AFMC/EN took the lead and solicited support from the AFMC staff, functional offices throughout the USAF, ASC/EN, AFRL, Air Force Global Logistics Supply Center (AFGLSC), Air Force Office of Special Investigations (AFOSI), Defense Logistics Agency (DLA), and Defense Contract Management Agency (DCMA) to address the issues of nonconforming titanium. The task force was formally established with an AFMC/EN briefing to the AFMC Commander on 18 August 2009. The primary mission of the team was to identify all safety-of-flight (SOF) and critical safety item (CSI) titanium parts procured to bar and plate specifications and to develop an action plan.

In consultation with ASC and AFRL, AFMC/EN determined that the following personnel should become members of the task force based on their expertise in aerospace structures and materials, and chartered them to develop the action plan:

- Thomas M. Fischer and Robert E. Reifenberg (HQ AFMC/EN)
- Charles A. Babish, IV (ASC/EN)
- Richard H. Reams and Mark S. DeFazio (ASC/ENFS)
- Lawrence M. Butkus and Jeffrey R. Calcaterra (AFRL/RXSA)
- Steven R. Thompson (AFRL/RXSC)

RISK MANAGEMENT APPROACH

The task force quickly determined that the first step should be to identify the titanium product forms that could be substituted with billet material, considering the ability to achieve overall product form dimensions (e.g., cut to size) and cost, compared to properly processed material.

Secondly, it was obvious that if parts had been fabricated from billet, material properties were not available to determine if strength or service life was affected. Billet material would have to be procured and tested to characterize its properties. The task force realized that it would be impossible to procure billet material for testing purposes that represented the absolute worst case (i.e., having the absolute lowest properties). To that end, the task force aimed at purchasing billet material for testing that has been subjected to processing that was close to the worst case (i.e., minimum amount of) processing as had been identified in previous studies. In addition, the task force also recognized that resources were insufficient to test the correct number of specimens to develop “full,” or statistically complete, handbook-quality material properties. Due to resource limitations, the task force planned and executed a test program that resulted in a set of material properties for the billet material and deemed the lowest value of each type of property the “reasonable lower bound.” It is the engineering judgment of the task force that these reasonable lower bounds represent the minimum properties that the majority of improperly processed titanium suspected to be in the DoD supply chain would be expected to exhibit. This approach is defined later in this report.

Another action the task force determined was necessary to define the scope of the problem was to identify the SOF and CSI parts in USAF aircraft manufactured from titanium. This step was expected to reduce the number of parts that would require scrutiny and keep the focus on safety. In addition, the task force suspected that not all titanium mills, vendors, suppliers, manufacturers, etc., were improperly substituting titanium material. Therefore, efforts were taken to identify which titanium material sources could be trusted for providing specification-compliant material.

Finally, after suspect product forms were identified, billet property data made available, safety critical parts determined, and trusted suppliers identified, the analyses could be updated to determine potential impact. Any resulting parts with reduced strength or service life would then require a risk assessment to determine the consequence of failure and the probability of occurrence in accordance with MIL-STD-882D (reference 9). High-risk parts would obviously require mitigating actions or possible replacement.

The task force finalized the risk management process steps as illustrated in Figure 1.

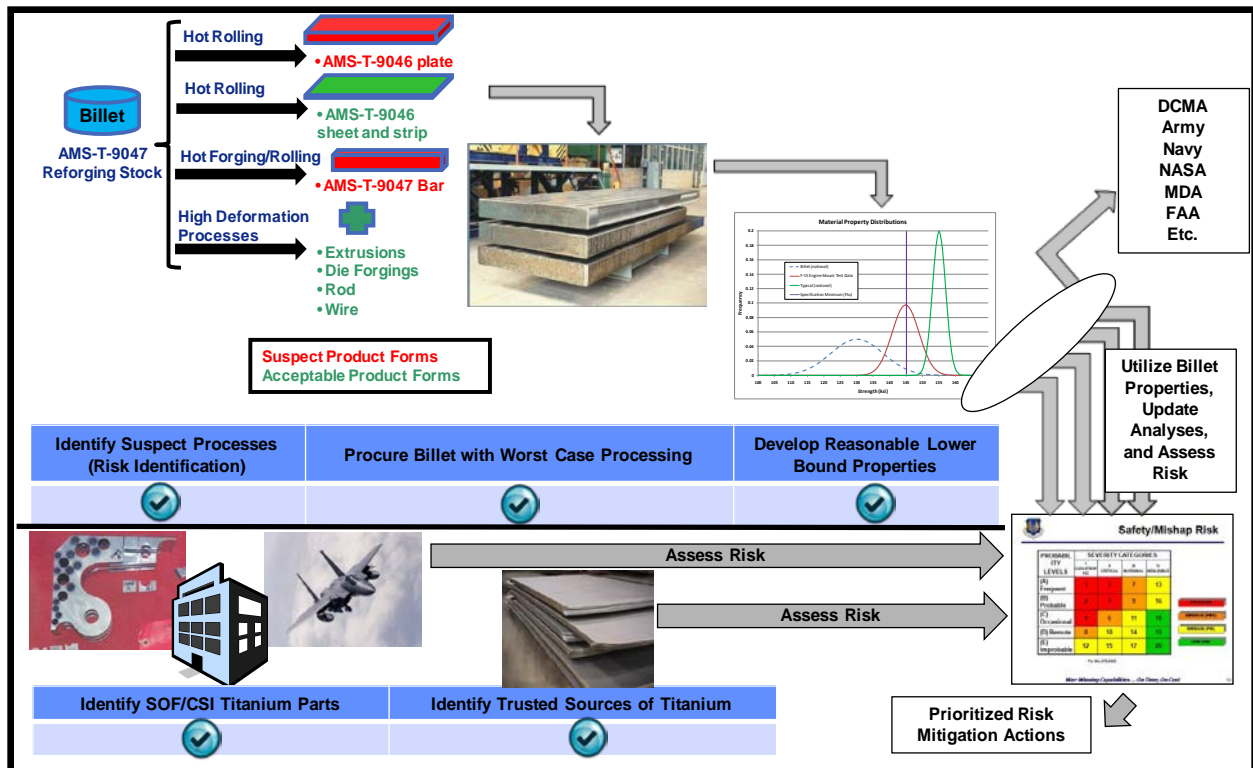


Figure 1 - Risk Management Approach

The process steps are repeated below for ease of reference:

1. Identify suspect processes and product forms
2. Procure billet material with worst-case processing
3. Develop reasonable lower bound mechanical properties
4. Identify SOF and CSI items manufactured from titanium
5. Identify trusted sources of titanium
6. Update analyses and determine any impacts to strength and service life
7. Determine risk in accordance with MIL-STD-882D
8. Identify and prioritize risk mitigation actions

The risk management approach was briefed by the task force and was approved by the AFMC Commander on 8 September 2009. Most importantly, a funding source for billet procurement and billet testing was also identified at the meeting. Several members of the office of Secretary of the Air Force (SAF), staffers of the Senate Armed Service Committee (SASC) and House Armed Service Committee (HASC), as well as DCMA were also apprised of the plan subsequent to the meeting.

An action item from the 8 September 2009 meeting was for the task force to inform the USAF program offices of the nonconforming titanium issue and to provide clear expectations about what they were required to accomplish. Out of this action grew a series of chief engineer briefings that were presented by the task force to ASC, the

three ALCs, and Electronic Systems Center (ESC). The key message of the briefings was to ensure that all program offices were aware of their responsibility to identify the SOF/CSI parts in their system, to update analyses after receipt of the billet test data, to determine risk, and to identify and prioritize risk mitigation actions (Steps 4, 6, 7, and 8 in the risk management approach). The task force would accomplish Steps 1, 2, 3, and 5. This report provides a summary of the four task force steps, but it does not present any findings or actions of the program offices.

In October 2009, the nonconforming titanium task force began to coordinate its activities across the Department of Defense (DoD), Navy (USN), Missile Defense Agency (MDA), National Reconnaissance Office (NRO), Army (USA), etc.), industry, the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA). As an additional means to disseminate information and obtain feedback on the risk management approach, a government/industry summit was sponsored by DCMA and the USAF in January 2010. Presentations were also made at Aircraft Structural Integrity Program (ASIP) Conferences in December of 2009 and 2010, and a follow-on industry summit was held in December of 2010.

IDENTIFICATION OF SUSPECT PRODUCT FORMS

The first step was to identify the titanium product forms that were most affected by billet substitution. If it was likely that billet could credibly be substituted for another product form, then that product form would be suspect. In other words, a product form would be suspect if it could be fabricated in a cost-effective manner by using basic cutting and milling processes. The task force carefully considered all titanium product forms used in aerospace systems as shown in Figure 2. (More information regarding this figure can be found in the appendix and in references 6 and 10.) All cast titanium products were immediately deemed low risk or “acceptable” since the casting process is completely different from the process for wrought products which begin with an ingot. It was also determined that sheet and strip material could not be made cost effectively by cutting billet. If attempted, it would not meet the distortion and flatness requirements and would have been rejected by the receiver of the material.

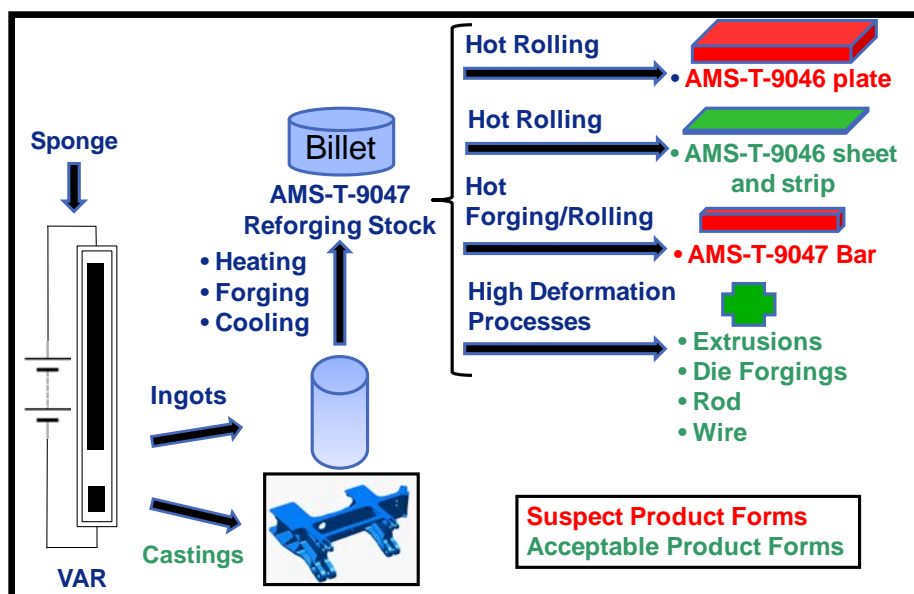


Figure 2 - Identification of Suspect Product Forms

All of the titanium product forms fabricated using high deformation processes (extrusions, die forgings, rod, wire, etc.) were highly unlikely to be fabricated directly from cut billet. For example, a common extruded section such as a “tee” would require an exorbitant amount of cutting, machining, etc.; therefore, there would be no cost-effective substitute for extrusions. Die forgings were also determined to be low risk since they usually have a complex outer geometry not conducive to simple manufacturing processes. However, the task force concluded that it would be cost effective to substitute billet for bar and plate because the cost of a cutting operation was significantly cheaper than the cost of rolling or forging operations required for converting billet to these product forms. Therefore, both bar and plate product forms were deemed the highest risk.

BILLET PROCUREMENT

Four different titanium billets were procured to develop reasonable lower bound material properties. The processing histories of these billets were chosen specifically to match as closely as possible the processing exhibited in the titanium AFRL tested in the 2006-2008 timeframe. This level of processing is believed to be typical of worst case (i.e., minimum amount of) processing that would yield minimum properties. The task force recognized there was some risk that less-processed and lower-quality titanium may exist in the DoD supply chain.

The first two billets purchased were Ti-6Al-4V³ material. This material was selected because it is the workhorse titanium alloy in the aerospace industry, and accounts for approximately 90 percent of the weight of titanium found on aircraft. The Ti-6-4 billets were both converted from ingot by Press Forge Co. in Paramount, CA. Both ingots were converted to 6.5" t (thickness) x 24" w (width) rectangular billets using their standard procedures. This size billet is one of the larger Press Forge cross sections produced. Press Forge sold this and smaller sizes to WT. WT subsequently cut the material and improperly certified it as bar or plate. The primary difference between the two Ti-6-4 billets is that the ingots were fabricated at different titanium mills.

The second two billets procured were Ti-6-6-2 material. This material was selected because it was thought to be more sensitive to billet conversion than Ti-6-4, and because F-15 engine mounts are made from this alloy. Since Ti-6-6-2 is a lightly used alloy, it was not possible to find two separate ingots from different melt sources in a timely manner. Instead, one ingot was converted to two different billet sizes using different hot working procedures. The first billet was converted to an 8" t x 12" w rectangular cross section that had approximately 50 percent area reduction, and the second was converted to a 4.5" t x 12" w rectangular cross section with approximately 70 percent area reduction. The Ti-6-6-2 billet conversion was done at Sierra Alloys in Irwindale, CA.

It is commonly understood throughout the industry that the amount of reduction is critical to developing mechanical properties. The 50 percent to 70 percent range represented the extremes of typical billet conversions.

³ Ti-6Al-4V denotes a titanium alloy with 6 percent aluminum, 4 percent vanadium, and the balance (90 percent) of titanium. This nomenclature is usually shortened to Ti-6-4.

DEVELOPMENT OF REASONABLE LOWER BOUND APPROACH

A material test program was established to develop mechanical properties for billet material. Since billet is an intermediate product form not intended to be used to make aerospace parts, billet properties data did not exist. The decision to refer to the mechanical properties as “reasonable lower bounds” was based on the fact that an insufficient quantity of material heats and lots were represented for the calculation of traditional MMPDS A- or B-, or even S-basis design allowables (see reference 7). However, the number of specimens tested (often in replicate) was significant enough to allow for statistical analyses where appropriate. Thus, the term reasonable lower bound (RLB) was chosen as the appropriate phrase to describe properties derived from the testing of multiple specimens from the two heats (per alloy) of material in this program. While these data did not meet the requirements for standard baseline property determination, they are sufficient to perform risk assessments.

For the testing described herein, analyses were performed to establish reasonable lower bounds for each property, excluding stress corrosion cracking (SCC). Statistical methodologies were utilized in the analysis of tensile strength (ultimate and yield), fatigue (S-N and ϵ -N)⁴, and fatigue crack growth rate (FCGR). Reasonable lower bounds for tensile ductility (elongation and reduction of area), elastic modulus, and fracture toughness are based on the lowest property in the population. Since stress corrosion cracking consisted of pass/fail testing, no further analysis was performed on the results from this testing.

Battelle (as secretariat for MMPDS) performed statistical analyses of tensile strength results using methodologies *similar to* those prescribed for MMPDS A-basis allowables. For this investigation, normal-distribution statistical methods were used for the determination of the reasonable lower bounds for ultimate tensile strength and tensile yield strength. In statistical terms, the reasonable lower bounds presented herein for tensile strength are the one-sided lower tolerance limit, representing a 95 percent confidence limit on the first percentile of the distribution. These preliminary RLB values were then compared against the material specification minimum values and MMPDS A-basis allowables (where available). The lower of these values was used as the final reasonable lower bound.

Battelle also performed fatigue analyses, again using procedures similar to those used in MMPDS. Equivalent stress (or strain) equations were developed on the data sets for both billet and plate. In order to establish lower bounds for the populations, 2-sigma curves were calculated from the equivalent stress (or strain) equations for each data set. Since established lower bound properties were not available for comparison, the control plate data developed under this program was used as the baseline. The life

⁴ S-N refers to a stress life curve wherein stress (S) is plotted against cycles to failure (N), and ϵ -N refers to a strain life curve wherein strain (ϵ) is plotted against cycles to failure.

factors for fatigue stated in the following sections are based on the worst case difference where billet had a lower life than plate.

UDRI performed statistical analyses for fatigue crack growth rate. Power-law curves initially were fit to the data populations to represent the mean behavior. In order to establish a bound on the population, 95 percent confidence limits were calculated for $\log (da/dN)^5$ at given values of $\log (\Delta K)^6$. As with fatigue testing, since no established lower bound properties existed for comparison, the control plate data developed under this program was used as the baseline. The life factors for fatigue crack growth rate stated in the following sections are based on the worst-case difference where billet had a lower life than plate. For the Ti-6-6-2 alloy, the F-15 engine mount data was also included in this analysis.

Fatigue & fatigue crack growth rate life factors that describe the relationship between the billet and control plate were provided by the task force for initial screening purposes only. These factors represent worst-case comparisons for two stress ratios (R)⁷ only. The factors approach 1.0 at certain regions of the life curves. Therefore, the task force recommended that if a program office's initial screening indicated a sufficient maintenance interval exists for the suspect titanium components, then no further analysis was required. However, if maintenance intervals were found to be unacceptable during the initial screening using these factors, then a program was encouraged to conduct further analysis using the full range of the test data provided by AFRL, and supplemented as appropriate with additional test data and analysis generated by the program office.

⁵ da/dN is the rate at which the crack length (a) grows with respect to cycles (N) and is the mathematical representation of the fatigue crack growth rate.

⁶ ΔK is the stress intensity factor range ($K_{\max} - K_{\min}$).

⁷ R is a ratio of minimum stress (S_{\min}) divided by maximum stress (S_{\max}).

Test Plan Development

Due to the rapid nature of the task effort, the technical experts within AFRL/RXS developed the initial test plan. They noted a need to interrogate specific static and dynamic properties; therefore, the test plan included tensile, fatigue crack growth rate, plane strain fracture toughness (K_{Ic}), S-N fatigue, and stress corrosion cracking. The task force developed the final test plan was in consultation with other government and industry experts at the initial industry summit in January 2010. Testing of the billet and control plate materials was accomplished according to Table 1. A comprehensive report written by AFRL contains all of the details regarding the test program (see reference 11).

Table 1 - Test Plan

Specimen Type and Orientation ⁸	Test Method
Tensile (L)	ASTM E8
Tensile (S)	ASTM E8
S-N Fatigue (L), R=0.05	ASTM E466
S-N Fatigue (L), R=-1	ASTM E466
S-N Fatigue (S), R=0.05	ASTM E466
S-N Fatigue (S), R=-1	ASTM E466
ϵ -N Fatigue (L), R=0.05	ASTM E606
ϵ -N Fatigue (L), R=-1	ASTM E606
ϵ -N Fatigue (S), R=0.05	ASTM E606
ϵ -N Fatigue (S), R=-1	ASTM E606
K_{Ic} (L-T)	ASTM E399
FCGR (L-T), R=0.1	ASTM E647
FCGR (L-T), R=0.7	ASTM E647
FCGR (S-L), R=0.1	ASTM E647
FCGR (S-L), R=0.7	ASTM E647
Axial SCC (L)	similar to ASTM G64
Axial SCC (S)	similar to ASTM G64

⁸ L refers to the lengthwise dimension of a billet (for plate, this orientation refers to the primary rolling direction); S refers to the thickness dimension of a billet or plate; T refers to the width. For fracture specimens (K_{Ic} and FCGR), the first letter corresponds to the loading direction and the second letter corresponds to the direction of the crack extension.

A specimen layout plan was developed for each billet received. Specimens for each of the tests shown were spread out through the billet so that the entire billet was interrogated along length, width, and thickness in order to determine if variability existed within the material. The test methodologies used in this investigation are listed in Table 2. With the exception of stress corrosion cracking, all of the tests were performed in accordance with applicable ASTM standards. All testing was performed in ambient laboratory conditions (approximately 72°F and 50 percent relative humidity).

Table 2 - Test Methodology

Test	ASTM Method
Tension (Modulus)	E 111-04 "Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus"
Tension	E 8/E 8M-08 "Standard Test Methods for Tension Testing of Metallic Materials"
Fatigue (force-controlled)	E 466-07 "Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials"
Fatigue (strain-controlled)	E606-04 "Standard Practice for Strain-Controlled Fatigue Testing"
Fatigue Crack Growth Rate	E 647-08 "Standard Test Method for Measurement of Fatigue Crack Growth Rates"
Fracture Toughness	E 399-08 "Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials"
Stress Corrosion Cracking	Similar to G 64-99 "Standard Classification of Resistance to Stress-Corrosion Cracking of Heat-Treatable Aluminum Alloys" Applied stress = 75% of specification tensile yield strength / 40 days 3.5% salt solution – alternate immersion (10 min wet / 50 min dry)

Specimens were removed from three planes through the thickness where possible: the two quarter points ($t/4$ and $3t/4$) and the midplane ($t/2$). The specimen location within the thickness is designated by either "A" ($t/4$), "B" ($t/2$), or "C" ($3t/4$). For short-transverse (S or S-L) oriented specimens, the location was determined by either the center of the gage length or the crack plane.

Test specimens were machined to the final required geometries. All of the geometries are in accordance with the applicable test method. All of the tensile, fatigue, and stress corrosion cracking specimens were fabricated using the same machine shop per specimen drawings provided by AFRL, in order to minimize possibility of variability due

to specimen machining. Since fatigue crack growth rate and fracture toughness specimens involve establishing a fatigue pre-crack after specimen machining, it was not necessary to utilize a single machine shop. Special care was given to the traceability of the specimen back to a general location within the billet. Test specimens were given a unique identification that would allow for this tracking.

A summary of the types and number of specimens is shown in Table 3. The Ti-6-6-2 specimen count (for both billet and control) includes testing performed for the F-15 engine mount studies.

Table 3 - Specimen Count

Property	Alloy	Number of Specimens	
		Billet	Control
F_{tu}	Ti-6Al-4V	301	40
	Ti-6Al-6V-2Sn	388	44
F_{ty}	Ti-6Al-4V	301	40
	Ti-6Al-6V-2Sn	388	44
% elongation	Ti-6Al-4V	301	40
	Ti-6Al-6V-2Sn	388	44
% reduction of area	Ti-6Al-4V	301	40
	Ti-6Al-6V-2Sn	388	44
E	Ti-6Al-4V	301	40
	Ti-6Al-6V-2Sn	388	44
K_{Ic}	Ti-6Al-4V	37	4
	Ti-6Al-6V-2Sn	18	2
S-N Fatigue	Ti-6Al-4V	108	35
	Ti-6Al-6V-2Sn	127	18
ε-N Fatigue	Ti-6Al-4V	86	37
	Ti-6Al-6V-2Sn	125	18
Fatigue Crack Growth Rate	Ti-6Al-4V	56	18
	Ti-6Al-6V-2Sn	60	13
Stress Corrosion Cracking	Ti-6Al-4V	53	4
	Ti-6Al-6V-2Sn	46	6

Test Materials

Due to the fact that billet material is intended to be an intermediate product form and not meant for use in component fabrication, a specimen orientation system needed to be established. The standard designations of longitudinal L, long transverse T, and short transverse S coordinate system were employed in this investigation in order to establish a consistency with plate and bar product forms. For these billets, the L-orientation was assigned to the billet length, the T-orientation to the billet width, and the S-orientation to the billet thickness.

Ti-6Al-4V

The first Ti-6-4 billet was purchased from Titanium Industries, Inc. The section received had nominal dimensions of 6.5" t x 24" w x 18.5" l and had been produced per the Aerospace Material Specifications (AMS) AMS-4928R (reference 12) and AMS-T-9047 (reference 10). The billet's pedigree traced back to an ingot produced by Howmet Castings. The billet was delivered in the mill-annealed, heat-treat condition.

Prior to test specimen extraction, the billet was subsectioned so that it could be subjected to nondestructive evaluation (NDE) using ultrasonic testing (UT). One relevant indication was noted during this evaluation and the location was removed from the billet for further examination. After the test specimens were machined, they were once again examined using NDE techniques. All specimens, except the fracture toughness, were examined using x-ray and fluorescent penetrant inspection (FPI). Fracture toughness specimens had UT and FPI examinations. Any resultant indications were noted and photographed for use in analysis of anomalous test results.

The second Ti-6-4 billet was also purchased from Titanium Industries, Inc. The section received had nominal dimensions of 6.5" t x 24" w x 45" l and had been produced per the AMS 4928R and AMS-T-9047 specifications. The billet's pedigree traced back to an ingot produced by ATI Allvac. The billet was delivered in the mill-annealed, heat-treat condition.

Upon receipt of the billet, a 4-inch wide section was cut along the length of the billet. The same orientation system was established for this billet. The face of this section through the thickness was machined to a 32 roughness average (Ra) surface finish and macro-etched to determine forging flowlines. No anomalous behavior was noticed during this examination. This section of billet was not used for subsequent mechanical testing.

Prior to test specimen extraction, the remaining billet was subsectioned so that it could be subjected to NDE using UT. The individual sections were designated as A through E and these designations were used in the specimen numbering schema. Some relevant, below threshold indications were noted during this evaluation, particularly in Section E. These areas were noted for further examination in the event of anomalous test results. After the test specimens were machined, they were once again examined using NDE

techniques. All specimens, except the fracture toughness, were examined using x-ray and FPI. Fracture toughness specimens had UT and FPI examinations. Any resultant indications were noted and photographed for use in analysis of anomalous test results.

The Ti-6-4 control plate used for this effort was purchased from Titanium Industries, Inc. The section of plate received had nominal dimensions of 4.25" t x 14" w x 12" l and had been produced per the AMS-T-9046 (reference 6) specification. The plate's pedigree traced back to an ingot produced by ATI Allvac. The plate was delivered in the mill-annealed, heat-treat condition.

Ti-6Al-6V-2Sn

Both Ti-6-6-2 billets were purchased from Sierra Alloys. The billets were fabricated for this program to AFRL/RXS prescribed thicknesses in order to produce two different levels of hot working in the material. Upon receipt from Sierra Alloys, the first billet had nominal dimensions of 8" t x 12" w x 80" l and the second billet had dimensions of 4.5" t x 12" w x 105" l. The billets had been produced per the AMS-T-9047G (reference 10) specification. The billets' pedigree traced back to an ingot produced by Howmet, and were delivered in the mill-annealed, heat-treat condition.

Upon receipt of the billets, a 2-inch wide section was cut along the length of the billet. The face of this section through the thickness was machined to a 32 Ra surface finish and macro-etched to determine forging flowlines. No anomalous microstructure was noticed during this examination. These sections of the billets were not used for subsequent mechanical testing. The same specimen orientation system, sub-sectioning, and NDE was used for these billets as was used for the Ti-6-4 billets.

The Ti-6-6-2 control plate used for this effort had originally been purchased for a similar investigation in 2005. The plate was obtained from RJ Enterprise, Inc. and had original nominal dimensions of 4" t x 12" w x 12" l and was produced per the AMS-T-9046 specification. The plate's pedigree traced back to an ingot produced by RMI and was delivered in the mill-annealed, heat-treat condition.

Testing Summary

AFRL published individual test reports for each billet of each alloy as testing was completed. (All of these reports are listed in reference 11). All testing was completed in October 2010 and a summary of the test results is shown in Table 4. Complete details of the reasonable lower bound and life factor test data and analysis can be found in reference 11.

Table 4 - Test Results

Property	Alloy	Reasonable Lower Bound / Life Factor	Difference from Specification Minimum or MMPDS Value
F_{tu}	Ti-6Al-4V	130 ksi	Same as MMPDS A-basis
	Ti-6Al-6V-2Sn	137 ksi	8 ksi lower than AMS-T-9046 (2"-4") 6 ksi lower than AMS-T-9047 (1"-3")
F_{ty}	Ti-6Al-4V	118 ksi	Same as MMPDS A-basis
	Ti-6Al-6V-2Sn	131 ksi	4 ksi lower than AMS-T-9046 (2"-4")
% elongation	Ti-6Al-4V	6.7%	3.3% lower than AMS-T-9046, 9047
	Ti-6Al-6V-2Sn	8%	Same as AMS-T-9046 (2"-4") Spec Min
% reduction of area	Ti-6Al-4V	10%	15% lower than AMS-T-9047 (<4") 10% lower than AMS-T-9047 (4"-6")
	Ti-6Al-6V-2Sn	19%	1% lower than AMS-T-9047 (L-orientation)
E	Ti-6Al-4V	15.3 Msi ⁹	0.7 Msi lower than MMPDS typical
	Ti-6Al-6V-2Sn	14.2 Msi	1.8 Msi lower than MMPDS typical
K_{Ic}	Ti-6Al-4V	59.8 ksi√in	N/A ¹⁰
	Ti-6Al-6V-2Sn	55.7 ksi√in	
S-N Fatigue	Ti-6Al-4V	0.61	N/A
	Ti-6Al-6V-2Sn	0.14	
ε-N Fatigue	Ti-6Al-4V	0.70	N/A
	Ti-6Al-6V-2Sn	0.69	
Fatigue Crack Growth Rate	Ti-6Al-4V	1X	N/A
	Ti-6Al-6V-2Sn	2X	

⁹ Msi is engineering shorthand for one million pounds per square inch (psi).

¹⁰ Minimum fracture toughness values are not required per the material specifications and are not published in MMPDS.

Differences between the RLB and specification minimums or MMPDS allowables are noted. Life factors noted indicate the fraction of the life of properly processed titanium that the improperly processed (billet) titanium exhibited. In other words, billet Ti-6Al-4V S-N fatigue specimens exhibited only 61% of the life exhibited by properly processed Ti-6Al-4V S-N fatigue specimens. The 2X life factor for FCGR is a comparison between billet and F-15 engine mount data (i.e., the growth rate was twice as fast), but the control plate was similar to billet.

TITANIUM MILL AND SUPPLIER REVIEW

The task force arranged visits to the major titanium mills in the United States to confirm that the mills were supplying properly processed titanium material. Many original equipment manufacturers (OEMs) for aerospace programs procure titanium material directly from the mills, so the task force anticipated that a large percentage of SOF and CSI parts could be eliminated from concern if they were fabricated with conforming material received from a mill. All of the sites visited represented every domestic producer of titanium with certification authority for bar and plate products. It was important that each site be visited since a Qualified Products List (QPL) or Qualified Manufacturers List (QML) for titanium producers does not currently exist.

Team membership consisted of quality and materials engineers from the USAF, USA, USN, MDA, DCMA, Boeing, Lockheed, Pratt & Whitney, and General Electric. The purpose of the visits was threefold. First, to determine if the sites had the equipment for producing titanium plate that was compliant with MIL-T-9046 and bar compliant with MIL-T-9047¹¹. Second, the team wanted to determine if company internal procedures could produce titanium products that meet the specification requirements. The third purpose was to determine if the quality systems employed are sufficient to ensure internal company procedures were consistently applied in the production of titanium bar and plate.

The team visited five companies at seven different sites. The dates of the visit and the associated trip reports are listed below:

Titanium Mills:

- TIMET Toronto OH, 9-11 March 2010 (reference 13)
- ATI/Allvac Monroe NC, 16-18 March 2010 (reference 14)
- RTI Niles OH, 23-25 March 2010 (reference 15)

Titanium Suppliers (reference 16):

- TIMET Precision Forged Products (PFP) Tustin CA, 18-19 May 2010
- ATI/Wah Chang Albany OR, 20 May 2010
- Sierra Alloys Irwindale CA, 17 May 2010
- Press Forge Company Paramount CA, 19 May 2010

TIMET (Toronto), ATI/Allvac, and RTI are the only three mills that domestically produce titanium ingot. These three companies in addition to ATI/Wah Chang and Sierra Alloys have the proper equipment for producing titanium bar and plate compliant with MIL-T-9046 and MIL-T-9047. TIMET PFP does not have forging equipment but relies on Press Forge to process titanium bar (but not plate). Each company used its own

¹¹ These two military titanium specifications are the predecessors of the AMS specifications.

proprietary processing for the material, but all proved capable of producing titanium bar and plate over a wide range of sizes.

A significant amount of thermomechanical processing data and manufacturing records were reviewed at each mill. All data indicated that each production system reliably and consistently produced specification-compliant material. The quality systems at each site were also reviewed; all systems indicated company production procedures were consistently followed and that employees were adequately trained. The overall conclusion of the team was that titanium bar and plate produced and certified by TIMET, ATI/Allvac, and RTI mills should not be considered suspect. No technical issues were found that would adversely affect system performance, and the material should be considered low risk.

At each supplier, thermomechanical processing data and manufacturing records were reviewed. Differences existed in each of the supplier's production systems, but the data indicated that each system produced specification-compliant material. The quality systems at each site were also reviewed, and all systems indicated that the company production procedures were consistently followed. The overall conclusion of the team was that titanium bar and plate produced and certified by ATI/Wah Chang and Sierra Alloys should not be considered suspect.

CONCLUSIONS AND RECOMMENDATIONS

The nonconforming titanium task force developed a risk management approach which included the identification of suspect product forms and a review of titanium mills and suppliers. These two actions significantly reduced the amount of suspect titanium material potentially in USAF systems. For the suspect bar and plate product forms, a test program was derived and billets of two common titanium alloys with representative worst-case processing were procured. From the billet material, reasonable lower bound material property data for static, durability, and damage tolerance analyses were developed. All of this information was disseminated to the USAF program offices to determine any structural strength and life impacts, and to assess the risk and implement appropriate mitigation actions.

The task force met its charter objectives primarily because it was comprised of people from the right organizations. These personnel had the knowledge and experience required to develop a focused risk management approach and secure the AFMC Commander's approval one month following the task force's formation.

The task force identified three key reasons for its success:

- A primary and overriding focus on the safety of USAF systems
- A small team with members from different organizations offering diverse expertise and experience
- High level support that facilitated the receipt of funding, the establishment of priorities, and the use of key facilities

Also, because the nonconforming titanium issue had wide-reaching impacts, the task force ensured effective communication to leadership and all affected stakeholders by using the following methods:

- Holding scheduled task force meetings
- Clearly delineating task force actions and program office actions to manage expectations
- Providing the Commander frequent updates
- Briefing program office chief engineers regularly
- Arranging for industry summits, which enabled collaboration between industry and other governmental agencies to disseminate the task force's risk management approach and to develop the billet material test plan
- Sharing briefings at conferences to ensure information was disseminated to a wide variety of engineers in the aerospace structures, aircraft systems, and materials disciplines.

CONCLUSIONS

1. Close cooperation and prompt reaction to material processing or fabrication issues is important to ensure that safety issues are quickly contained and efficiently resolved.
2. The task force recognized the industry lacks a quality assurance method that can guarantee a material has been processed properly. Current industry practices document the process flow with paperwork records that travel with the material, and these records are used for material certification and acceptance. As such, the records are subject to errors and inaccuracies. Ideally, a reliable NDE technique should be available to evaluate the microstructure of a material and ensure it was properly processed before being used to manufacture aerospace hardware.
3. The titanium specifications do not adequately describe the proper documentation of all processing steps performed in the conversion from ingot to finished product. The material certifications should contain all mechanical and thermo-mechanical work performed on the material.
4. During discussions with other government and industry representatives, the task force concluded that there have been misinterpretations of the current titanium specifications. The most significant pertain to the maximum size limitations of billets, i.e., the minimum amount of deformation required during the forging process. (As an example, AMS-T-9047A lists the width or cross-section area for bar and reforging stock, but neither identifies the value as a linear dimension or an area, nor specifies the maximum allowable thickness.)
5. Use of industry specifications has left the government without any authority over the content of the specifications. The government occasionally attends meetings concerning changes to the specification, but usually does not have a vote in the decision process. Re-establishment of military specifications would enable strict government control over the specification.
6. The task force also concluded that a single point of contact who can answer questions on proper interpretation of the specifications does not exist. This was not the case with the legacy military specifications wherein a single military office was identified and possessed the requisite technical expertise to answer any interpretation questions.
7. With respect to the accomplishment of its tasking, the task force also realized that AFRL's in-house materials expertise proved to be invaluable in terms of conducting NDE, performing mechanical testing, obtaining reasonable lower bound properties, and serving as technical experts in a number of forums as discussed in this report.

8. Finally, as mentioned in the Titanium Mill and Supplier Review section, a qualified product and or material list (QPL and/or QML), does not exist for the industry. As such, each time a material quality issue arises, a review or audit of the supplier's facilities is required, which is inefficient, time-consuming, and expensive.

RECOMMENDATIONS

1. Participate with industry organizations and develop procedures to prevent future nonconforming material substitutions and to quickly report them if they occur.
2. Develop a reliable NDE technique to evaluate microstructure as a quality assurance method to ensure proper material processing.
3. Revise the AMS titanium specifications to state that all material processing steps are required to be shown on the material certifications.
4. Revise the AMS titanium specifications to clearly explain size limitations of billet material.
5. Reinstate military versions (MIL-T-XXXX) of industry titanium specifications such as AMS-T-9046 and 9047. Update the specifications with the latest material property data and include Recommendations 3 and 4.
6. Maintain world-class materials expertise at AFRL.
7. Retain AFRL's in-house capability to support future quick-reaction efforts.
8. Write a QPL and/or QML for titanium producers.

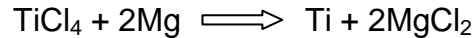
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BACKGROUND ON TITANIUM FABRICATION

A top-level description of titanium materials and processes leading to fabrication of aerospace parts is provided in this section. At the beginning of the process, naturally occurring titanium dioxide (TiO_2), commonly known as “rutile,” is chlorinated to form titanium tetrachloride (TiCl_4). Titanium tetrachloride is subsequently distilled to remove any impurities. Using the common Kroll reduction process, titanium tetrachloride is reacted with magnesium to separate the titanium using the following chemical reaction:



The purified titanium, called “sponge,” is used to produce wrought or cast titanium products. The sponge material is typically melted using the vacuum arc remelting (VAR) process. The cold hearth melting process is also used in the industry, however, VAR is the most prevalent process used. As a minimum, most aerospace material is “double melted” for homogeneity. Alloying elements can be added during sponge crushing or melting. Most products undergo a final melt using VAR.

The VAR process is illustrated in Figure 3. Sponge is crushed, compacted, and welded to form electrodes, and a direct current is passed through the electrode to produce an electric arc which melts or consumes the electrode. This process must be done in a vacuum and/or inert atmosphere because of the high reactivity of titanium with oxygen and nitrogen. Finally, the molten titanium can be poured into cylindrical crucibles to make ingots, or poured into molds to make castings (see Figure 3).

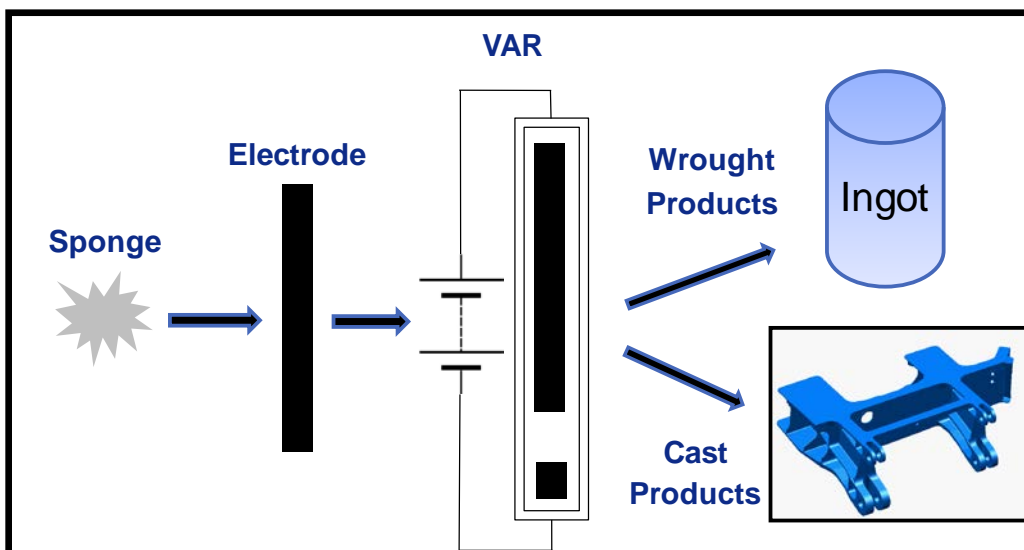


Figure 3 - Titanium Wrought and Cast Products

To get to bar and plate finished products, the ingots require a great deal of mechanical work to develop the necessary material properties. The ingot is first heated to soften the material, then forged or deformed in large presses, and finally allowed to cool to produce a billet as seen in Figure 4. Frequently, the ingot is mechanically cut to smaller sizes in order to fit within the dimensions of the press or to meet the limitations of the material handling equipment. The billet material is referred to as reforcing stock per the material specifications, and as such, is an intermediate product not suitable for making aerospace products. The billet or reforcing stock is usually worked to a size that can be accommodated by equipment/machinery used for subsequent processing.

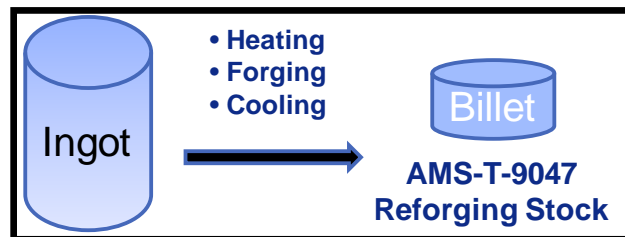


Figure 4 - Titanium Billet

Subsequent processing of the billet is required to transform it into a finished product that can be used to fabricate an aerospace component. Several process examples and several finished products are illustrated in Figure 5. As seen in this figure, rolling, forging, extruding, etc. processes are required to impart additional mechanical work into the material to develop the requisite material properties.

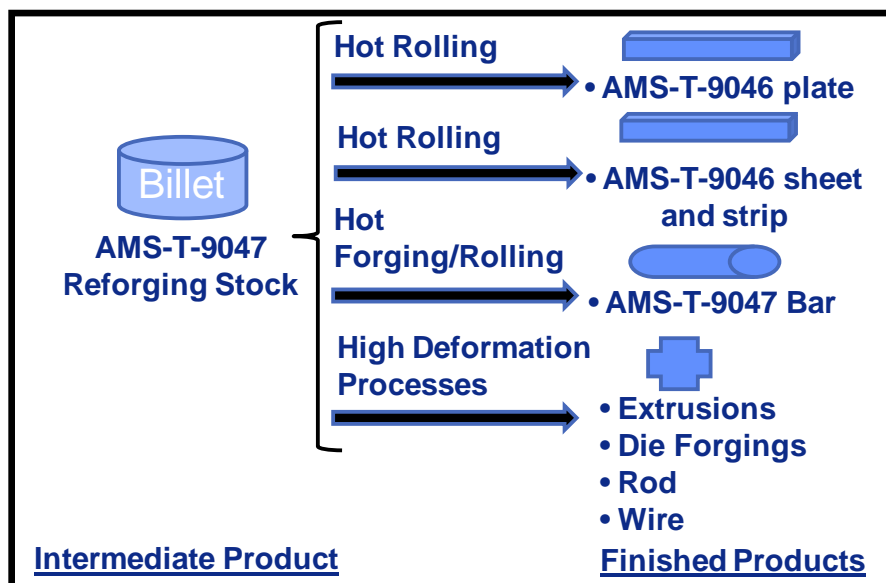


Figure 5 - Titanium Finished Products

Titanium plate and sheet is fabricated by hot rolling the billet through progressively narrower rollers to produce the desired thickness. By definition, titanium plate is at least 0.1875 inches thick and sheet is 0.1874 inches or thinner. Strip material is simply sheet material that has been cut along the width dimension. Titanium bar comes in many different varieties and shapes – as examples, billet material can be rolled along the length dimension to produce round bar, or billet material can be forged along the length dimension to produce square or rectangular bar. High deformation process is a broad, generic term to cover manufacture of other products and other shapes. Regardless of the type of titanium finished product, it is important to remember that additional processing of the billet is necessary before it is usable to fabricate an aerospace component or part.

LIST OF ACRONYMS AND ABBREVIATIONS

AFGLSC	Air Force Global Logistics Supply Center
AFMC	Air Force Materiel Command
AFOSI	Air Force Office of Special Investigations
AFRL	Air Force Research Laboratory
ALC	Air Logistics Center
AMS	Aerospace Material Specification
ASC	Aeronautical Systems Center
ASIP	Aircraft Structural Integrity Program
ASTM	American Society for Testing and Materials
CSI	Critical safety items
DCIS	Defense Contract Investigative Services
DCMA	Defense Contract Management Agency
DLA	Defense Logistics Agency
DoD	Department of Defense
ε	Strain
E	Elastic Modulus
ESC	Electronic Systems Center
FPI	Fluorescent Penetrant Inspection
F_{ty}	Yield tensile strength
F_{tu}	Ultimate tensile strength
FAA	Federal Aviation Administration
FCGR	Fatigue Crack Growth Rate
GIDEP	Government-Industry Data Exchange Program
HASC	House Armed Services Committee
K_{Ic}	Plane Strain Fracture Toughness
MDA	Missile Defense Agency
MMPDS	Metallic Materials Properties Development and Standardization
N	Cycles
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation
NRO	National Reconnaissance Office
OEM	Original Equipment Manufacturer
QML	Qualified Manufacturers List
QPL	Qualified Products List
R	Stress Ratio
Ra	Roughness average
RLB	Reasonable Lower Bound
S	Stress
SAF	Secretary of the Air Force
SASC	Senate Armed Services Committee
SCC	Stress Corrosion Cracking
SOF	Safety-of-flight
UDRI	University of Dayton Research Institute
USA	United States Army

USAF	United States Air Force
USN	United States Navy
UT	Ultrasonic Testing
UTC	Universal Technology Corporation
VAR	Vacuum Arc Remelt
WT	Western Titanium